SUMMARY OF STUDIES
FOR A SOLAR OPTICAL TELESCOPE IN SPACE: 1968-1976

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PREFACE

When the Spacelab becomes operational, a new generation of solar research activities will become feasible. The Spacelab will enable solar physicists to achieve high spatial and spectral resolution, to conduct high-speed observations of rapidly evolving solar phenomena, to simultaneously view common objects with several instruments covering wide spectral ranges, to recover photographic film, and to post-flight calibrate their instruments. The full utilization of the Shuttle capabilities is, of course, contingent upon the development of telescopes with longer focal lengths, larger apertures, more stringent alignment tolerances, more precise pointing requirements, and more complex focal plane apparatus than those presently used in space.

NASA has sponsored a number of studies on the design requirements of large space-borne solar telescopes of the near IR/visible/UV spectral range. These investigations have been carried out by several organizations and have addressed varied initial specifications with primary apertures ranging from 65 cm to 150 cm and with platforms including the Spacelab, the Apollo Telescope Mount (ATM), and free-flying satellites. A balloon-borne Design Verification Unit (DVU) was also considered in one study.

Additional analysis will be required to finalize the design of a solar telescope for Spacelab. Since the preliminary reports are of considerable number and volume, a concise summary of their most significant design recommendations can serve as a valuable reference when further analysis is undertaken.

It is of particular importance to identify the initial assumptions of each investigation, the areas of consensus and of disagreement among the studies, and the components or subsystems which may require significant redevelopmental effort.

This summary was compiled by Drs. J. Bremer and R. Kaul of Operations Research, Inc. under the direction of Dr. W. Neupert and Mr. C. Stouffer of GSFC. Valuable inputs were contributed by Dr. R. Dunn of the Sacramento Peak Observatory and Mr. J. Mangus of GSFC.

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I. INTRODUCTION

1-1. BACKGROUND

Observations of the sun at high angular resolution and in many spectral regions of interest are difficult or impossible to conduct from Earth. Strong solar heating of the Earth's atmosphere produces pronounced seeing degradations, and, since the sun is an extended low-contrast source, the correction of the resultant images is a formidable task. The Earth's atmosphere also prevents observations at UV wavelengths where many of the most significant solar phenomena may be investigated.

Since the early 1960's, NASA has sponsored a program of space-borne solar observations including rocket flights, the OSO series of satellites, and the ATM/Skylab manned flights. These investigations have revolutionized our understanding of the fundamental physical processes of energy production in the sun's interior, the transport of this energy through the solar atmosphere, and its ultimate dissipation as radiation, acceleration of plasma, and the solar wind.

Solar investigations benefit greatly from the real-time evaluation of images by a skilled observer and from the ability to respond quickly to unpredicted targets of opportunity such as solar flares. Consequently, NASA plans to make manned observing platforms available for large solar telescopes. In the late sixties, a 65-cm telescope was designed (but not flown) for the ATM/Skylab flights. More recent efforts have addressed a

meter-class optical telescope for Shuttle-based solar observations in the 1980's. It is anticipated that the experience gained in Shuttle-based investigations will ultimately be applied to a free-flying, Shuttle-launched manned solar observatory.

1-2. SCOPE OF SURVEY

The telescope designs which are summarized in this document have been generated in response to a variety of initial requirements. Investigations by the Jet Propulsion Lab. (JPL) and Ball Brothers Research Corp. (BBRC) have considered 65 cm telescopes for deployment on the Apollo Telescope Mount (ATM). A series of reports by Itek considered a 150 cm telescope for use in a Shuttle-launched, free-flying Large Solar Observatory (LSO), a 100 cm telescope for Shuttle-based observations, and a 100 cm balloon-borne Design Verification Unit (DVU) for flight tests of the Shuttle telescope. A report by Mega Analytical Research Services, Inc. treated the design of 65-cm and 100-cm Shuttle-based telescopes. A Sacramento Peak Observatory (SPO) report considered a 125-cm aperture telescope which would be modular in design and which could be applied to both solar and non-solar investigations.

Analyses of two major subsystems were also included in this survey: a study of the primary mirror by Perkin-Elmer and a structural design study by Boeing Aerospace Co.

The studies summarized in this review are listed below:

1. Photoheliograph Definition Study, ITEK, 1973; including
   a. "Executive Summary."
   b. Volume I, "Summary."
   c. Volume II, Book I, "150 Centimeter Photoheliograph for LSO Mission."
   d. Volume II, Book II, "100 Centimeter Photoheliograph for Shuttle and Balloon Missions."
   e. Volume II, Book III, "Advanced Technology and Project Planning."
2. Photoheliograph, Jet Propulsion Laboratory, 1968-1969 including:
   a. "Primary Mirror Development," 750-7.

b. "Optical System," 750-8.
c. "Alignment System," 750-11.
d. "Structure, Mounting, and Mechanisms," 750-13.
e. "Structural Development," 750-19.

3. C.I.T., Photoheliograph Definition Study, Ball Brothers Research Co., 1971.

4. Final Report for the Helioscope, Mega Analytical Research Services, Inc. 1975.

5. Facility Definition Team: 1.25 meter Shuttle Optical Telescope Briefing, R. Dunn, et. al., (SPO), 1976.

6. 100 cm Solar Telescope Primary Mirror Study, Perkin-Elmer, 1975.

7. Structural Design Configuration Study, Boeing Aerospace Co.

8. Helioscope: Telescope in Space, H. Zirin, et al, (JPL), 1968.

The primary object of this review is to tabulate the basic recommendations of several solar telescope studies. A preliminary matrix, listing some of the basic optical parameters, was compiled by Dr. R. Dunn of SPO and forms the basis of Table I-1. From this table it is apparent that a strong consensus exists on the configuration of the telescope and on its fundamental dimensionless parameters. The tables presented in the next section address the basic approach of each study to the telescope design as well as to the design of critical subsystems. These subsystem problems include the material, coating, configuration, mounting, launch locks, and thermal control of the primary mirror, the structure of the main telescope and the instrument bay, the mechanisms for radiation rejection, thermal control, and meteoroid shielding, and methods of maintaining image quality by proper alignment and by image motion compensation.

TABLE I-1

OPTICAL PARAMETERS OF SOLAR TELESCOPE DESIGNS

Parameter \ Study Organization	JPL	BBRC	ITEK	ITEK	ITEK	MEGA	MEGA	SPO
Platform	ATM	ATM	LSO	SHUTTLE	BALLOON	SHUTTLE	SHUTTLE	SHUTTLE
Year of study	1968-69	1971	1973	1973	1973	1975	1975	1975
Primary aperture (CM)	65	65	150	100	100	100	65	125
Configuration	GREGORIAN	GREGORIAN	GREGORIAN	GREGORIAN	GREGORIAN	GREGORIAN	GREGORIAN	GREGORIAN
System f/no	50	50	40	40	40	30	45	25
Primary f/no	3.85	3.85	3	3	3	3	4	3.6
Secondary Magnification	13	13	13.3	13.3	13.3	10	11.3	6.9
Obscuration ratio	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.12
Field of view (ARC-MIN)	3.2	3	4	6	6	3	3	6
Angular Resolution (ARC-SEC)	0.2@ 500NM	0.2	0.1@ 200NM	0.3@ 300NM	limited by atmosphere	0.16@ 485NM	0.10@ 485NM	0.10
Spectral Range (NM)	150 to 600	200 to 700	200 to 1100	200 to 1100	200 to 1100	270 to 650	270 to 650	150 to 1100
Alignment Tolerances								
Axial (MM)	-	.003	.003	Scale 150	Scale 150	.0025		
Recenter (MM)	.036	.060	.022	Scale 150	Scale 150	.10		
Tilt (DEG)	.0125	.10	.0023	Scale 150	Scale 150	.20		
Stabilization	1 $\widehat{sec}$/sec	1 $\widehat{sec}$/sec .01 sec/exp	.01 $\widehat{sec}$ RMS	.0125 $\widehat{sec}$ RMS	.0125 $\widehat{sec}$ RMS	-		
System Wavefront Error	0.1λ @ 500NM	0.1λ	0.1λ @ 532.8NM	0.1λ @ 632.8NM	0.1λ @ 632.8NM	- -		
Primary Mirror Wavefront Error	0.05λ @ 500NM	0.05λ	0.04λ @ 532.8NM	0.04λ @ 632.8NM	0.04λ @ 632.8NM	- -		

II. TABULATION OF DESIGN RECOMMENDATIONS

The tables presented in this section give a brief account of the approaches to the broad system design problems which were advocated in each of the studies. The tables also spell out the pre-specified design requirements and indicate other techniques which were considered. If a subject area was discussed in a given report, a brief entry is present in the appropriate location in the matrix. Page-references to the original report are also included to enable the reader to locate additional information.

Below are listed the major areas of investigation:

Table	Area of Investigation
II-1	Basic Telescope Design
II-2	Heat Rejection Mirror
II-3	Primary Mirror Configuration
II-4	Primary Mirror Materials
II-5	Primary Mirror Thermal Control System
II-6	Primary Mirror Mount
II-7	Primary Mirror Launch Lock
II-8	Main Telescope Structure
II-9	Instrument Bay Structure
II-10	Thermal Control Technique
II-11	Meteoroid Shield
II-12	Alignment System
II-13	Image Motion Compensation Technique

These tables contain detailed information on the approach of each study group to the major design problems, identifying, where appropriate, the preliminary design requirements, preferred techniques, rejected techniques, and other options considered. Readers who desire only a cursory overview are referred to Section III, where the major areas of agreement and disagreement among the studies are summarized.

TABLE II-1

BASIC TELESCOPE DESIGN

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
ITEK, 150-cm LSO, 1973 (pg. 4-1 to 4-10)	• 1200-11,000Å • Minimum scattered light and polarization change by keeping the number of reflections down.	• On-Axis Gregorian Best suited to dump solar energy	• Newtonian with eccentric primary, rejected because of length • On-axis Cassegrain — rejected because of large obscuration or high scattered light levels • Eccentric Cassegrain — rejected because of solar heating of the secondary and nonuniform heating of the primary. • Eccentric Gregorian is sensitive to the misalignment of mirrors but the best alternative to the on-axis Gregorian. • On-axis Gregorian, eccentric ellipse secondary, poor image quality. • Gregorian with minimum eccentric primary, slightly tipped secondary. The second best alternative to the on-axis Gregorian.	
ITEK, 100-cm, Shuttle, 1973	• Resolve 0.3 arc-sec objects	• On-axis Gregorian f/40, 6 arc-min. FOV, Exposure time 0.5 to 0.02 sec (pg. 4-2).		
ITEK, 100-cm, DVU, 1973	• Same as 100-cm Shuttle.			

TABLE II-1 (continued)

BASIC TELESCOPE DESIGN

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
JPL, 65-cm, 1968	• 0.2 arc sec @ 5000 Å. • 1500 to 6600Å Spectral range	• Gregorian, f/50, 3.2 arc min FOV. • Gregorian because of thermal design f/50 for plate scale matching and low convergence for H-alpha filters. • Plate scale is 6.3 arc sec per mm.	• Cassegrain - rejected because of out-of-focus image on the primary mirror causing thermal gradients. (pg. 3, 750-8) • Tertiary design - high flux densities on secondary mirror and large obscuration. • Baker Variation of JPL Design - eliminated because of high heat flux on diagonal flat causes image degradation.	
BBRC, 65-cm, Def. Study, 1971	• 0.2 arc sec resolution • 3 arc min FOV	• Gregorian, f/50, film format 24 x 24 mm. • Folder Gregorian with heat dump mirror.	• Cassegrain - rejected because of heat load on secondary and degradation of mirror coating due to solar UV. • Newtonian - Gregorian - small diagonal mirror exposed to intense heat. Also the diagonal mirror presents alignment problems	• Off-axis Gregorian has several advantages, but would require advances in manufacturing technique and would require more precise alignment.
MEGA, 1975	• 2700 to 6500A	• On-axis Gregorian	• Cassegrain - solar furnace effect	
SPO, 1976	• Multiuse: solar, planetary, galactic extrogalactic.	• 125 cm, f/3.6 primary • Dual mode operation: f/25 Gregorian or f/3.6 Newtonian • 6 arc-min FOV • Rastering capability		• Single telescope for solar & stellar observation could produce a FOV of 0.2° (vs. stellar goal of 0.5°) and could meet the remainder of the stellar telescope requirements. • Use of solar telescope for high - resolution planetary observations appears attractive.

TABLE II-2

HEAT REJECTION MIRROR

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
ITEK, 150-cm LSO, 1973		• Heat Shield Mirror Use Ag to minimize absorption. Incident flux = 7.3×10^3 Btu/hr. Use radiating fins for cooling the mirror.		• Use heat pipes as thermal radiators or a liquid loop.
ITEK, 100-cm Shuttle, 1973		• Heat Shield Mirror Low α coating, heat pipes to space radiator, electric heaters to balance for nonoperation (pg. 13-1).		
ITEK, 100-cm DVU, 1973		• Same as 100-cm Shuttle.		
JPL, 65-cm 1968		• Heat stop mirror diameter of hole = 0.36 cm.		
MEGA, 1975		• Heat stop mirror with Ag overcoat.		
BBRC, 65-cm ATM		• BeCu No. 10 mirror for high conductance to heat sink. Mirror overcoated.		
SPO, 1976		• Heat stop mirror limits FOV to 6 arc-min in Gregorian Configuration.		

TABLE II-3

PRIMARY MIRROR CONFIGURATION

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER OPTIONS CONSIDERED
ITEK, 150-cm LSO, 1973 (Volume II, Book I)	• Three-point edge mount. • Sun-synchronous orbit. • 1/80 λ rms surface required. • f/3. (pg. 5-1).	• Monolithic specular core light weight, blackened surfaces in core holes 1. weight saving over solid (775 lbs. vs. 1500 lbs). 2. less sag. 3. disadvantage of greater cost.	• Light weight, backcooled monolith. • Heat-probe, actively cooled. • Exotic coating, transmission or reflection. • Water-cooled. (pg. 5-6).	• Solid mirror is acceptable alternative, cheaper and easier to build, but heavier (pg. 5-6).
ITEK, 100-cm Shuttle (Volume II, Book II, Ch. 1-13).	• Scaled from 100 cm (see pg. 5-2).	• Solid mirror for reasonable weight and low cost. • Multi-point back support necessary during fabrication (pg. 6-2 to 6-6) (pg. 5-12).		• Specular core lightweight mirror is acceptable.
ITEK, 100 cm DVU (Volume II, Book II, Ch: 14-30).	• Maximum sag of 0.01 λ. • Mirror orientation from "on edge" to "pointing up" without exceeding deflection. • Temperature 70° ± 20°F (pg. 18-1).	• Solid mirror (as above). • 34 back supports required. • Active liquid system (mercury rings in bezel) (pg. 18-1 to 18-6).	• Passive liquid (high pointing errors). • Counterweight- (high complexity, little damping, not servo controlled). • Active air (high risk, servo bandwidth coupling to fine tracking).	
JPL: 1968, Photoheliograph: Structure, Mounting, and Mechanisms (750-13) and Primary Mirror Development (250-7) and Optical System (750-8)	• Mushroom mirror 65 cm diameter, spiral channel active cooling. • Coolant a uniform distance from face, minimized consistent with fabrication (750-13: pg. 15 and 16).	• Fluid flow - laminar from inside to outside (750-7, pg. 12). • Mushroom 1 in thick at rim, 4 in total thickness at hub, one inch back ribs. • Mushroom mirror found to minimize thermal distortion. • Three pieces: surface, back plate with groove, and hub (750-8: pg. 37).	• Mushroom with no back ribs. • Solid mirror blank. • Cervit - can't be fuzed and retain shape (750-7: pg. 8).	• Displacement of miniscus due to thermal distortion is less than half of a tapered plane mirror with same rim & hub dimensions (750-7: pg. 5)(and 750-8 pg. 20).

TABLE II-3 (Continued)

PRIMARY MIRROR CONFIGURATION

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER OPTIONS CONSIDERED
BBRC, 1971	• f/3.85 primary (pg. 4-2). • Hub supported mirror. • Surface figure 0.01 λ rms (p. 5-8).	• Invar collar, bonded to mirror hub (p. 5-8).		
MEGA, 1975	• High dimensional stability, low thermal distortion. • λ/50 surfaces (p. 38). • Stem supported primary (p. 43).			
Perkin-Elmer, 1975, 100-cm Solar Telescope, Primary Mirror Study	• Choose from among three configurations: solid, standard lightweight and mushroom (from Goddard Drawing #GD1297646 of 4/1/74). • Evaluate according to Manufacturing Metrology, Manufacturing Risk, and Ultimate Quality Assessment. • Require λ/40 rms surface quality (pg. 4). • Final Selection based upon a matrix of criteria and weights (pg. 39).	• Solid (+) 1. Least gravity deflection (pg. 7) (+) 2. Least costly, easiest to form. (+) 3. Least sensitive to shock. (-) 4. Heaviest. (-) 5. Large thermal expansion. • Counterweight support for zero g simulation (pg. 8-11).	• Mushroom (-) 1. Large number of mounting points required. (+) 2. Low weight. (-) 3. Highest manufacturing risk. (+) 4. Best thermal stability (-) 5. Greatest self-weight deflection (pg. 7).	• Lightweight 1. Least dependent on variations in material properties (core samples may be used to better predict thermal properties.
SPO, 1976	• Solid mirror, 125 cm, 20 cm thick.			

TABLE II-4

PRIMARY MIRROR MATERIALS

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER OPTIONS CONSIDERED
ITEK, 150-cm, LSO, 1973 (Volume II, Book I)	• Low thermal expansion coefficient.	• Aluminimum coating. • ULE mirror material (pg. 5-11).	• Exotic coatings (Si & Ge) for thermal control (pg. 5-6). • Silica mirror rejected for high thermal expansion (pg. 5-16).	• Cer-Vit also acceptable for mirror blank (pg. 5-15).
ITEK, 100-cm, Shuttle (Volume II, Book II Ch. 1-13).	← Same as above →			
ITEK, 100-cm DVU (Volume II, Book II Ch. 14-30).	← Same as above →			
JPL, Primary Mirror Development 750-7.	• Minimize TDI = $\alpha\rho C\rho/K$ where α=coef. of thermal expansion K=thermal conductivity $C\rho$=specific heat ρ=density (also 750-8: pg. 26). • Maximize E/ρ where E=elastic modulus (750-7: pg. 1). • Primary mirror requirements: 1. 1/50 λ rms errors. 2. Thermal distortion < 1/20 λ. 3. Systematic wavefront error over 2 arc min. < 1/8 λ. 4. Gravity release error < 1/40 λ.	• ULE - amorphous, therefore two pieces can be fuzed to form cooling fluid channel (750-7, pg. 16).	• Stainless st., titanium (high TDI) nickel, brass. • Copper, silver (too soft) • Magnesium, tungesten (fabrication problems). • Tantalum, graphite (low E/ρ) (750-7, pg. 4). • Beryllium, 1. can't be formed with channels internal to mirror, 2. requires Kanigen coating - poor performance in near U.V. (750-7, pg. 12).	• Super Invar further investigations necessary (750-7 pg. 6). Cer-Vit can't form channel since structure is crystaline (750-7, pg. 6). • <u>Areas needing additional study:</u> 1. Mirror coating degradations due to UV & charged particles. 2. Reflection measurement. 3. Primary mirror materials – long term stability of: ULE, Cer-Vit, and beryllium.
BBRC, 1971	• 0.028 λ fabrication error budget. • 0.014 λ thermal error budget (pg. 4-24).	• Cer Vit or ULE mirrors (pg. 4-25). • Aluminum with MgF_2 overcoat or "enhanced" aluminum for mirror surfaces (pg. 4-26).	• Metals, esp. beryllium, figuring and coating problems (pg. 4-25).	

TABLE II-4 (Continued)

PRIMARY MIRROR MATERIALS

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER OPTIONS CONSIDERED
Perkin-Elmer, 1975 100-cm Solar Telescope, Primary Mirror Study (pg. 2, 20-22).	• Low expansion mirror material: 1. CerVit blank. 2. Al coating with MgF_2 overcoat.			
MEGA, 1975	• low thermal expansion ULE or Cer-Vit (pg. 118). • Reduction of gradients. • Mirror concepts: 1. CerVit lightweight, specular core. 2. ULE lightweight. 3. ULE solid. 4. ULE mushroom. (pg. 121)	• Radiative coupling to cold plates located behind the mirror. • Flash copper (i.e. reflective surface) on back of primary (pg. 112). • Specular cold plate.	• Lightweight ULE (not explained).	
SPO, 1976	• Al coating with MgF_2 overcoat.			• Tungsten coating for observations at 500 Å – 1000 Å.

TABLE II-5

PRIMARY MIRROR THERMAL CONTROL SYSTEM

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
ITEK, 150-cm LSO, 1973 (Volume II, Book I)	• Thermal degradation <0.025 λ	• Radiation from blackened surfaces in core holes to cold-plate (pg. 5-5). • *Cold-plate coupled to* space-viewing radiator by a heat pipe. • Active heating when primary does not view sun.	• Water-cooled mirror rejected because of weight, reliability, and maintainability, and uncertain state of the art. • Exotic coatings rejected due to poor transmissivity at desired wavelengths and uncertain state of the art (pg. 5-6).	• Further study necessary on added heat load due to degradation of mirror surface (pg. 4-37).
ITEK, 100-cm Shuttle, 1973 (Volume II, Book II, Ch. 1-13)		• Radiation from blackened back of primary to cold-plate. • Cold-plate coupled to space-viewing radiator by a heat pipe. • Active heating when primary does not view sun.		• Fluid loop cooling is possible but not desirable.
ITEK, 100-cm DVU, 1973 (Volume II, Book II) Ch. 14-30)	• Temperature $70^{o} \pm 20^{o}F$ (pg. 18-1)	• Cold-plate, heat pipe radiator system (as above) (pg. 18-6 to 18-9). • Summary indicates mirror has sufficient heat capacity to permit use without cooling mechanism in DVU (Volume I, pg. 4).		• Thermal pluming problems (Volume I, pg. 3).
JPL Primary Mirror Development (750-7), 1968	• Internal channel behind primary mirror face	• Laminar flow of active cooling fluid: → mirror → radiator → pump • Two heaters in loop to stabilize temperature 1. Coarse (110W) for sun-off period 2. Fine (5W) for mirror stabilization (750-%, pg. 16)	• Radiative cooling claim backplate must be $-40^{o}F$ to maintain $70^{o}F$ front mirror face (750-%, pg. 6).	
BBRC, 1971	• Cold shell at $10^{o} \pm 1.7^{o}C$ • 61 Watts absorbed when viewing sun (pg. 4-33)	• Annular mirror around primary and large diameter to prevent vignetting • Conduction through mirror with radiation to shroud should provide adequate cooling.	• Active fluid (as in JPL Report)	

TABLE II-5 (Continued)

PRIMARY MIRROR THERMAL CONTROL SYSTEM

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
MEGA, 1975	• Low thermal distortion	• Annular heat stop mirror around primary to prevent uneven heating during off-axis pointing (pg. 93). • Front aperature large enough to avoid vigetting of primary (pg. 93). • To reduce gradients in specular core mirrors, put flash copper on insides of back of mirror or make a specular cold plate behind the mirror (pg. 112).		
Perkin-Elmer 100-cm Solar Telescope, Primary mirror study, 1975 (pg. 20-28)	• $\lambda/50$ rms wavefront error ($\lambda/100$ rms surface) due to on-orbit thermal distortions • Approach to design: 1. Minimize non-linear thermal gradients 2. Minimize effects of non-uniform coefficient of thermal expansion 3. Minimize effects of temporal heat load changes (pg. 23-25)	• Solid mirror has lowest non-linear thermal gradients because of its uniform thermal resistance. • If lightweight mirror is used, specular core will minimize non-linear gradients. • Mushroom mirror, being thinnest, is least sensitive to variations in coef. of thermal expansion. • Solid mirror preferable for large thermal time constant (p. 27). • Mushroom preferred for thermal reasons-small variation in coefficient of thermal expansion.	• Mushroom mirror has large non-linear axial gradients. • Mushroom and lightweight mirrors have small thermal time constants (p. 29).	

TABLE II-6

PRIMARY MIRROR MOUNT

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER OPTIONS CONSIDERED
ITEK, 150-*cm* LSO, 1973 (Ref. Table 6-1)	• *Minimum mount* interaction loads	• Axial, 3-*point mount*. Produces least mirror rms wavefront error for unit thermal soak load. A-frame mount may be acceptable. Superinsulation and heater control of mounts (pg. 8-5).	• *Multipoint mount*. Requires impractically low diametral thermal gradients to hold mirror wavefront.	• *Tangent bar 3-point mount* • Kinematic
ITEK, 100-cm Shuttle 1973		• Axial, 3-point mount. (See above)		
ITEK, 100-cm DVU 1973		• Bezel providing back and edge support 36 back supports are employed to remove the gravitational effects. Active liquid support selected to allow mirror tilting. Edge support was mercury ring to keep edge stresses low. Thermostatic control with heaters.		• Other back support system; Mechanical counterweight Passive liquid Active air
JPL, ATM Photoheliograph 1968 (Ref. pg. 24 of 750-13)		• Ring and Truss &Hub Support • 6 radial trusses running between outer ring and the center tube surrounding the hub of the mirror.		
BBRC, ATM Photoheliograph 1971 (Ref. pg. 2-8)		• Hub Support. • Mirror supported by center, no edge supports when on-orbit Polyurethane epoxy interface between hub and support truss (4 - 67 & 5 - 8).		
MEGA 1975		• *Hub Support (pg. 43)*.		
SPO 1976		• A-frame with 6 degrees of freedom.		

TABLE II-7

PRIMARY MIRROR LAUNCH LOCK

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
JPL, ATM Photoheliograph, 1968 (Ref. pg. 17 of 750-13)		• Circumferential Shoes 36 shoes each subtending 5 degrees of the mirror circumference, or two ½ circumference bands. Thermal release mechanisms.	Hydraulic shoe releases were ruled out because of volatile leakages.	Explosive releases ruled out because of man-rated ATM.
BBRC, ATM Photoheliograph, 1971		• Not required except in torsion (pg. 4-67) • Circumferential Shoes 12 shoes, each subtending 12 degrees of the beveled mirror circumference. Each shoe spring loaded and released by a motor actuated band.		
MEGA, 1975		• Radial Caging Locks (pg . 46).		
SPO, 1976		• Launch locks required.		

TABLE II-8

MAIN TELESCOPE STRUCTURE

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER OPTIONS CONSIDERED
ITEK, 150-cm LSO, 1973 (Ref. Table 6-3)	• Secondary Decenter for 0.01 RMS wave-front error is 0.08 min (pg. 4-5).	• Athermalized truss Consists of struts and rings which show small changes with heat soak. However close tolerances and spacing required. (Invar struts and titanium rings or graphite-epoxy struts and aluminum rings.)		• Shell • Rod and Shell
ITEK, 100-cm Shuttle 1973 (Ref. page 7-1 & 9-1)	• Spacing change less than 1.2 x 10^{-4} inch to secondary and 10^{-3} inch to heat shield mirror.	• Same as above, but employs graphite-epoxy (page 13-2).		
ITEK, 100-cm DVU 1973 (Ref. pg. 19-1)		• Same as 100-cm Shuttle, but requires a vacuum tank around entire assembly with main aperture and heat dump windows.		
JPL, ATM Photoheliograph 1968 (Ref. pg. 24 of 750-13)		• Athermalized truss configuration Fabricated of thin wall invar tubing. They calculate 18 structural resonant frequencies below 100 Hz (pg. E-1, 750-19).	• Double layered Al housing with internal material, because of organ pipe resonance between 35 and 200 Hz, lateral bending due to nonuniform heating.	
BBRC ATM Photoheliograph 1971 (Ref. pg. 4-55 to 4-61 Fig. 5-6)		• Athermalized truss configuration • Fabricated of invar and aluminum, proportioned to maintain tube length. Six rings (Al) supported by 12 invar tubes. They suggest end opening to minimize differential heating (pg. 4-58). Lowest resonant frequency near 30 Hz (pg. 4-63).	• Invar Monocoque • Requires support rings for mounting subassemblies and may require extra rings to stiffen the skin. Also some stress relieving required following fabrication.	

TABLE II-8 (Continued)

MAIN TELESCOPE STRUCTURE

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER OPTIONS CONSIDERED
MEGA, 1975		• Solid Cylinders, graphite-epoxy (pg. 117).		
Boeing, 65 & 100-cm Structural Design Study.	• Depth of focus = $\pm$ 0.5 mm. • Decenter = 0.06 mm. • Tilt = 0.1 deg. • Pri-Sec Spacing = 0.003 mm (pg. 36).	• Graphite Epoxy Cylinders with rings: • Laminate structure: -0° plies of HMS: 25% $\pm$ 45° plies of AS, 934 resin: 50% 90° plies of AS, 934 resin: 25% • Can take loads, has low outgassing and is thermally stable.		• See Table 3-9 (pg. 40). • Did <u>not</u> calculate longitudinal (circumferential) temperature gradients (pg. 45). <u>More work required</u> to determine <u>decenter</u> due to off-axis loads.
SPO, 1976		• 3-Sided Span with honeycomb structure • 3-position secondary turret		

TABLE II-9

INSTRUMENT BAY STRUCTURE

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER OPTIONS CONSIDERED
ITEK, 150-cm LSO 1973 (Ref. Table 6-4)	• No change in optics spacing	• Athermalized truss configuration Consists of struts and rings which show small changes with heat soak. Close tolerance and critical spacing requirements. (Invar struts and titanium rings).	• Metering rod configuration • Shell configuration (Both approaches rejected because of lack of accessibility to internal components)	
ITEK, 00-cm Shuttle 1973 (R /. pg. 13-112)		• Low expansion instrument assembly • Graphite-epoxy		
ITEK, 100-cm DVU 1973 (Ref. pg. 25-1)		• Low expansion instrument assembly • Athermalized, graphite-epoxy		
BBRC ATM Photoheliograph 1971 (Ref. pg. 4-72)		• Strong box-like construction Yields high moment of inertia which allows use of low strength materials, yields high resonant frequencies and reduces case strains. Aluminum construction okay because large depth of focus allows movement due to thermal expansion (pg. 5-64).		
SPO 1976		• Instruments placed at either primary focus or Gregorian focus. • Instrument mounting surfaces on 3-sided spar structure.		

TABLE II-10

THERMAL CONTROL TECHNIQUE

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
ITEK, 150-cm LSO, 1973				
ITEK, 100-cm Shuttle, 1973	• Minimum temp. gradients and reasonable ambient temperatures.	• Low emittance coating (α/E = 0.12/0.04) on meteoroid shield yields minimum truss temperature gradients. (pg. 9-2).	• High emittance (α/E = 0.22/0.88) without insulation yields too much truss length change (pg. 9-2).	• Low emittance (α/E = 0.12/0.04) with insulation. • High emittance (α/E = 0.22/0.88) with insulation (pg. 9-1).
ITEK, 100-cm DVU, 1973	• Minimum temperature gradient across window and reasonable reliability.	• 70^{0}F mirror, telescope in vacuum. The thermal control systems will be the same as those aboard the Shuttle.	• 70^{0}F mirrors, helium gas because of high temperature gradient across window. • -70^{0}F mirrors, atmosphere because of pluming at mirrors, water condensation and preconditioning required on ground. • -70^{0}F mirror, helium gas because of the preconditioning required.	
JPL, 65-cm, 1968		• Superinsulation around truss. • Spiral cooling loops in primary and on heat dump mirror (pg. 29, 750-13).		
BBRC, 65-cm ATM, 1971		• ATM Fluid Loop for cooling shield. Radiative cooling for secondary and primary. Secondary cooled by conduction through truss then radiation (pg. 4-37). A shroud extends 52 in front of primary mirror to minimize differential heating of the truss (pg. 5-58). • A BeCu annular mirror surrounds the primary mirror to reduce off-axis pointing differential heating. The secondary pad is made of BeCu for good heat conduction.		

TABLE II-10 (Continued)

THERMAL CONTROL TECHNIQUES

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
MEGA, 1975		• Balloon model Primary mirror = 21°C with 18 ± 2 watts. Secondary mirror = 20 ± 1 watts. Folding mirrors = 18 ± 1 watts (pg. 108). • Shuttle model Evaluated radiative cooling of solid mirror. Results indicate that this technique is okay if shell contains Shuttle coolant (pg. 109).		
SPO, 1976		• Thermal shroud encloses structure.		

TABLE II-11

METEORIOD SHIELD

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
ITEK, 150-cm LSO, 1973 (Ref. Table 6-5)		• Double-wall construction. Provides more efficient meteoriod protection at 60 to 80% weight savings over single-wall construction.		• Single-wall construction.
ITEK, 100-cm Shuttle, 1973 (Ref. pg. 13-2)		• Single-wall construction. Probably changed because thermal results best when meteor shield had no insulation and $a/\varepsilon = 0.12/0.04$ (pg. 9-2).		
ITEK, 100-cm DVU, 1973 (Ref. pg. 19-1)		• Vacuum Tank. Replaced meteoroid shield and must have window.		
JPL, 65-cm, 1968		• Superinsulation around athermalized truss. The aluminized mylar film is wrapped around the truss to give insulation plus mechanical damping.		
BBRC, 65-cm ATM, 1971		• Contained in ATM cold shell at 10°C (pg. 4-31).		
SPO, 1976		• Thermal, meteroid, and purge shroud encloses telescope structure.		

TABLE II-12

ALIGNMENT SYSTEM

(Focussing, Decenter, Tilt)

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
ITEK, 150-cm LSO, 1973 (pg. 9-4).	• Designed for structural deflections of ± 0.05 inch.	• A-frame actuator on the secondary mirror. The A-frame (pg. 9-6) technique is employed because of redundance and low weight. A sequential on-off servo drive for the actuators is employed. A spherical mirror decenter sensor target with its center of curvature at the primary mirror focus is used to decouple from the tilt sensor (pg. 9-20). The sensor locations are shown in Figure 9-7.	• Motion of focal plane instruments. This would require movements of the order of 50 millimeter, which are quite large. • Motion of primary mirror. The primary mirror changes the boresight and is much heavier than the secondary.	• A total of 21 techniques were considered. See Table 9-2, pg. 9-5 for details.
ITEK, 100-cm Shuttle, 1973		• Same design as 150-cm above (pg. 10-1 and 13-2).		
ITEK, 100-cm DVU, 1973	• 0.02 λ rms wavefront degradation = 3 μm in spacing.	• Same design as 150-cm above (pg. 22-1).		
JPL, 65-cm, 1968	• Decenter = 0.08 mm • Secondary tilt = 0.75 arc min (pg. vii, 750-8A). • Depth of focus = ± 2.5 mm. • Spacing error = 0.001 cm.	• Beam Splitter on Primary Mirror (pg. 65; 750-8A). For roll, mount a spherical mirror on the primary and null the signal between the sensor and the primary mirror. • The translation and tilt are then measured by autocollimation and boresight techniques Translation can be measured to ± 0.0005 cm and tilt to ± 0.42 arc min.	• Standard Autocollimating Technique.	

TABLE II-12 (Continued)
ALIGNMENT SYSTEM
(Focussing, Decenter, Tilt)

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
BBRC, 65-cm ATM, 1971	• Decenter = 0.06 mm (pg. 4-14). • Spacing error = 0.003 mm (pg. 4-17). • Secondary mirror tilt = 45 arc sec. • Depth of focus = 0.5 mm.	• Movement of Secondary Mirror Pad for decenter and tilt correction. Pulsed GaAs laser emits at 9000 A in secondary pad. Then a four edge detector and a quadrant detector. The signals must be processed to determine tilt and decenter errors (pg. 5-23). • Focus done with image dissector tube monitoring the medium spatial frequency content of the image and moving the secondary mirror (pg. 5-27).		
MEGA, 1975	• Decenter = 0.1 mm. • Tilt = 0.02 deg. • Primary to Sec. spacing = 0.0025 mm. • Depth of focus = 0.25 mm.			
SPO, 1976		• Primary-Secondary Alignment Detector. • CCD Trackers for stability.		

TABLE II-13

IMAGE MOTION COMPENSATION TECHNIQUE

STUDY	DESIGN REQUIREMENT	PREFERRED	REJECTED	OTHER CONCEPTS CONSIDERED
ITEK, 150-cm LSO, 1973 (pgs. 7-1 to 7-13)	• 0.01 arc sec stability P, Y, R.	• Relay optics tracking 1. Does not affect the quality of the wavefront even over large excursions. Use image correlation tracker in the focal plane to actuate pierolectrics on folding mirror (pg. 7-13). 2. Roll stabilization by a star tracker perpendicular to LOS (pg. 7-13).	• Move focal plane instrumentation. Difficult because instruments would have to be accurately synchronized. Also this approach has no advantages over secondary and relay mirror adjustments.	• Stabilize entire vehicle. • Stabilize helioscope. • Stabilize primary mirror. • Stabilize secondary mirror.
ITEK, 100-cm Shuttle, 1973	• 0.0125 arc sec stability on LOS.	• Articulate relay mirror (pg. 8-1). 1. Must gimbal at the C.G. 2. Employ a correlation tracker. 3. Range of relay mirror is ± 2 arc sec.		
ITEK, 100-cm DVU, 1973 (pg. 25-2)	• 0.0125 arc sec stability.	• Similar to 100-cm and 150-cm.		
BBRC, 65-cm ATM, 1971		• Movement of second folding mirror 1. Image is Fourier analyzed as a function of position. 2. Mirror is articulated to maintain fixed Fourier coefficients at a given image position.		
MEGA, 1975		• Movement of second folding mirror. 1. Image is Fourier analyzed as a function of position. 2. Mirror is articulated to maintain fixed Fourier coefficients at a given image position. • Movement of folding mirror (pg. 52).		
SPO, 1976		• Use of IPS to achieve to Avoid IMC (if possible). • Combined rastering and IMC systems.		• Possible use of correlation tracker.

III. CONCLUSIONS

In spite of major variations in the initial specifications of the different studies, a strong consensus has emerged on the basic configuration of a solar telescope. This unity of approach is intrinsic to the nature of solar observations from space and is therefore relevant to any solar optical telescope design.

A meter class solar telescope is of necessity a complex instrument which must serve in a wide variety of experiments to be cost-effective. It should therefore be designed with a broad spectral range, with emphasis on the near ultraviolet wavelengths which are strongly absorbed by the earth's atmosphere. All telescope designs required good optical throughput from a short wavelength cutoff of 150 - 270 n.m. to a long wavelength cutoff in the visible or the near IR. Ability to focus and monitor at one wavelength and to collect data at another wavelength was also considered highly desirable. As a consequence of these requirements, the designers chose all-reflecting optics with aluminum surfaces and magnesium fluoride overcoating. Special purpose refractive elements such as field flatteners may be used if required for individual experiments. Alternative mirror coatings were considered for Shuttle sorties with restricted spectral coverage: silver for the visible and infrared only, tungsten for the range from 50 to 100 nanometers.

The sun is a highly radiant, extended, low-contrast observational target. Designers of a solar telescope are therefore willing to trade off optical speed to obtain a modulation transfer function (MTF) which is close

to the diffraction limit. The system focal length is made sufficiently long that the MTF of the detector (usually the granularity of photographic film) produces only negligible degradations of the system MTF. A large system f/number also facilitates the use of narrow-band spectral filters for investigations of the profiles of emission and absorption lines. The telescopes designed exclusively for solar investigations have system focal ratios in the f/30-f/50 range. The multi-purpose instrument designed by the SPO research team has a f/25 system focal ratio with output relay optics capable of extending as far as f/100.

To achieve a long system focal length with acceptable physical dimensions, a two-element telescope is required. To minimize thermal problems, all designers selected a Gregorian configuration in preference to a Cassegrain. A meter class solar telescope must dump the overwhelming majority of incident solar radiation if it is to avoid extreme heating. A Gregorian telescope may be fitted with a field stop at its primary focus, admitting a small angular field to the secondary mirror and rejecting the remainder of the sun's image with a heat dump mirror. Since the heat dump mirror serves as a field stop only, it may undergo thermal distortions without degrading the focal plane image. In contrast, a Cassegrain telescope concentrates an intense radiation flux density (of order one hundred solar constants for typical parameters) on the secondary mirror. The Gregorian telescopes considered in this summary admit fields of view of 3-6 arc minutes in diameter to secondary optics, rejecting the remainder of the sun's 32 arc-minute image and therefore subjecting the secondary mirror to only a few solar constants.

The speed of the primary mirror is optimized in a tradeoff; a fast primary increases the intensity of the solar flux concentrated on the field stop, is more costly to fabricate, and requires more stringent alignment tolerances but a slow primary increases the length of the telescope. The solar telescope studies proposed primary speeds of f/3 to f/4 and magnifications of 10X to 13.3X. The SPO telescope study selected an f/3.6 primary speed and a magnification of 6.9.

Since high MTF is a critical design requirement, obscuration must be kept as low as possible. Use of a folding mirror to remove the secondary from the optic axis (thereby reducing obscuration) was rejected because it would

produce solar furnace heating of this folding mirror. An off-axis Gregorian was considered promising, but was rejected for the present because the manufacture of the primary mirror would involve high cost and risk, because aberations would be more severe, and because more stringent alignment tolerances would be imposed. An on-axis Gregorian configuration with an obscuration ratio in the range 0.2-0.3 was selected in each investigation. The SPO modular telescope would have an obscuration ratio of 0.12 in the Gregorian configuration.

A Shuttle-borne telescope in low earth orbit will not view the sun continually. The primary mirror must be able to maintain its figure under variations of radiation loading. Since it is manufactured in a one-g environment and deployed in a zero-g environment, its gravity release deformation must also be kept within acceptable limits. All studies recommended the use of a primary mirror material with a low coefficient of thermal expansion: ULE or Cer-Vit. Beryllium was rejected because of its high cost, low scratch quality, and requirement for precise thermal control (see Appendix A).

The image quality requirements may be as severe as 0.01 arc sec. Image motion compensation is necessary to achieve this performance goal. The consensus indicates that a focal plane correlation tracker is required to correct for the drift of the image by movement of a folding mirror. This technique is discussed in Appendix B.

3-1. AREAS OF CONSENSUS ON SOLAR-DEDICATED GREGORIAN TELESCOPES

All studies conducted prior to 1976, i.e., all except the work of the SPO team, addressed the development of a diffraction-limited, solar-dedicated telescope. The strong consensus which has emerged on the basic design of such an instrument is illustrated in Figure 3-1. It is significant to note the unanimity of the basic optical layout: an on-axis Gregorian telescope with a heat dump mirror at the primary focus and folding mirrors between the secondary mirror and the focal plane. The quantitative consensus is also quite strong, especially in light of the differing initial constraints. The basic dimensionless (i.e., scale independent) optical parameters are in good agreement:

- System speed: f/30 - f/50
- Primary speed: f/3 - f/4
- Magnification: 10 - 13.3X
- FOV: 3 - 6 min diameter
- Linear obscuration ratio: 0.2 - 0.3

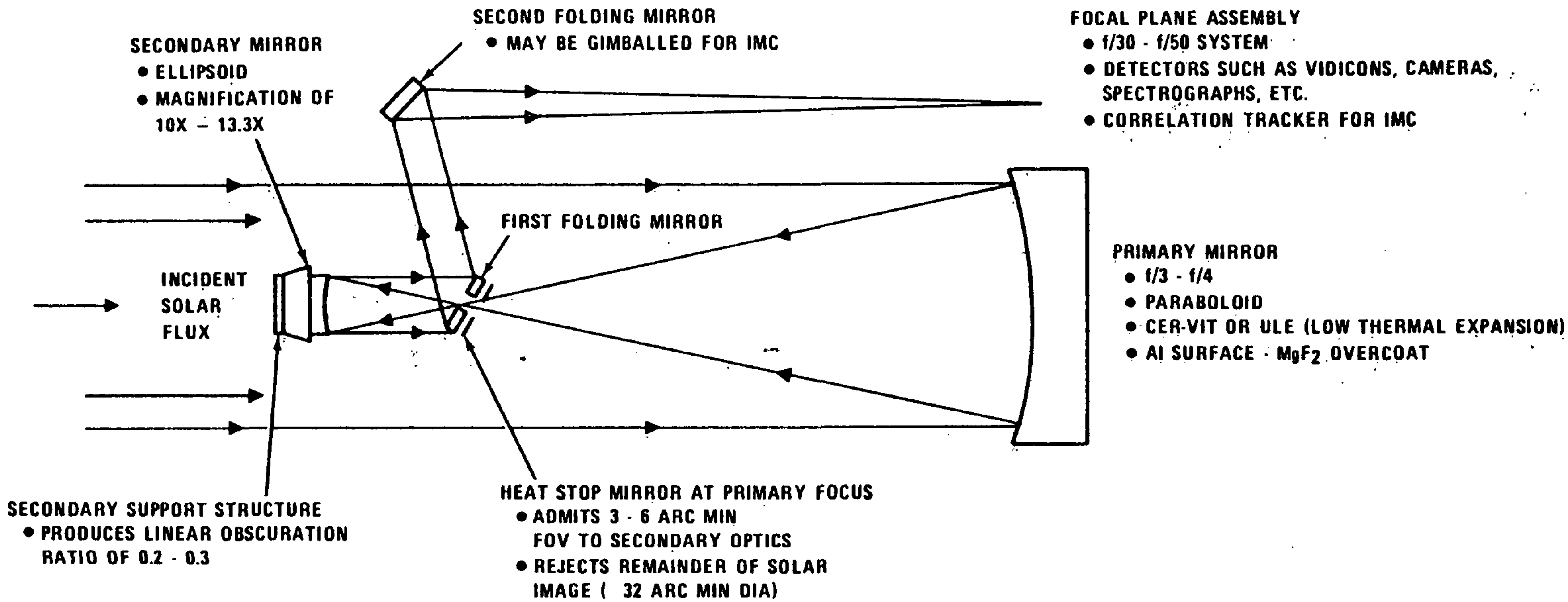


FIGURE III-1. CONSENSUS ON BASIC DESIGN OF A SOLAR-DEDICATED TELESCOPE

The telescope proposed by the SPO team could be deployed in either a Newtonian or a Gregorian configuration, and could raster its primary mirror. In spite of these greatly different requirements, its optical parameters in the Gregorian mode differ from the consensus only in having a slightly smaller magnification and, consequently, a slightly lower f/number.

3-2. AREAS OF DISAGREEMENT

No consensus was reached on two basic problems in the design of the primary mirror: its basic geometric configuration and its thermal control mechanism. The three basic geometries which were considered for the mirror blank were solid, lightweight, and mushroom. Although it is the heaviest configuration, the solid mirror was chosen frequently for its low cost, ease of manufacture, and shock resistance. Most of the reports recommend that cooling of the primary mirror be achieved by radiative coupling between the blackened back surface of the primary mirror and a cold plate which is coupled to a space-viewing radiator. (If a lightweight configuration is selected, specular cores are used to minimize non-linear thermal gradients in the mirror.)

All of the studies recommended the use of a laser diode image detector system to maintain the primary-secondary alignment, i.e. to insure that the optic axes of the two mirrors are coincident. The placement of the elements varies from study to study.

There is also disagreement on the construction of the basic telescope structure. Most of the reports advocate the use of an athermalized truss, but the use of a graphite-epoxy cylinder is also possible.

The studies indicate that the basic optical subsystems may be constructed:

- The manufacturing tolerances, thermal distortion, and gravity release of the primary mirror may be controlled to achieve a good optical surface quality.
- The heat shield mirror may be constructed to reject the bulk of the solar flux without vignetting of the image due to thermal distortion.
- A primary-secondary alignment system may be constructed to compensate for thermally-induced distortion the metering structure.

There was, however, no convincing demonstration that the entire telescope, performing as a closed-loop system and interfacing with the Shuttle, could achieve the ultimate image quality of a meter-class, diffraction-limited instrument. The uncertainties are centered about the problem of obtaining optimal focus, which requires the adjustment of many parameters and the evaluation of their effects on the quality of the image. The extended, low-contrast, temporally-variable images which are characteristic of solar observations have yet to be duplicated in breadboard tests of alignment and IMC systems. The fact that such systems have performed satisfactorily with static "picket-fence" targets is no guarantee of their capacity to function in realistic solar missions.

APPENDIX A

INDICES OF THERMAL QUALITY FOR PRIMARY MIRROR MATERIALS

(Based on memoranda to Dr. W. Neupert, GSFC, from Dr. J. Bremer, ORI)

Several of the Solar Telescope Studies considered the thermal response of the primary mirror to varying heat loads in their evaluation of candidate primary mirror materials and geometries. The JPL study contains a discussion of materials in which the highest priority is the minimization of the thermal distortion index (TDI), which is defined as:

$$\text{TDI} = \alpha(C/K)$$

where α = Coefficient of linear thermal expansion
C = Volume specific heat
K = Thermal conductivity

The TDI is inversely proportional to the thermal diffusivity, indicating that a short thermal time constant is desirable. The JPL study states that it is desirable for the mirror to reach thermal equilibrium as soon as possible following the onset of a thermal soak. In contrast, the Perkin-Elmer study indicates that steady-state conditions will never be approached and therefore advocates maximizing the thermal time constant, i.e., minimizing the thermal diffusivity. A complex model of the thermal properties of a mushroom mirror is presented in the BBRC report.

In view of the differing approaches and conclusions of these studies, we have created a simple but realistic one-dimensional model to predict the thermal behavior of a solid primary mirror. The mirror is assumed to be a one-dimensional structure with its back surface coupled to a heat sink at constant temperature T_0. At time t = o, the mirror is in equilibrium at temperature T_0. At times t > o, the front surface of the mirror is exposed to radiation and absorbs a uniform heat per unit area. Time dependent expressions are derived for the temperature profile of the mirror and its total change in thickness.

We define:

x: $x = 0$ at back surface of mirror

$x = s$ at front surface of mirror

T = Temperature

α = Coefficient of linear thermal expansion

K = Thermal conductivity

C = Volume specific heat

$D = K/C$ = Thermal diffusivity

$F = (dQ/dt)_{x=s}$ = Power absorbed per unit area at front surface of mirror

The heat flow equation is:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{D}\frac{\partial T}{\partial t}$$

Initially, the entire mirror is at temperature T_0, producing the boundary condition:

$$T(x, t = 0) = T_0 \text{ for all } x$$

For all t > 0, the thermal gradient at the front surface is fixed, producing the boundary condition:

$$\left.\frac{\partial T}{\partial x}\right|_{x = s} = \frac{F}{K}$$

The temperature of the back surface if fixed, producing the boundary condition:

$$T\ (x = 0,\ t) \ = \ T_o$$

The general physical solution of the heat flow equation is:

$$T\ (x,\ t) = \sum_{\lambda} A_{\lambda} e^{-\lambda^2 Dt} \sin\lambda x + \sum_{\lambda'} B_{\lambda'} e^{-(\lambda')^2 Dt} \cos\lambda' x + C_o + C_x x$$

where the A_{λ}'s, $B_{(\lambda')}$'s, and C's are constants.

Application of the boundary conditions restricts the solution to the form:

$$T\ (x,\ t) \ = \ T_o + (F/K)x + \sum_{n=o}^{\infty} A_n \sin\left[\frac{(n + \frac{1}{2})\pi x}{s}\right] \exp\left[\frac{-\pi^2 (n + \frac{1}{2})\ Dt}{s^2}\right]$$

The final boundary condition, that the temperature of the entire mirror be T_o at $t = 0$, further requires that:

$$(F/K)x \ = \ -\sum_{n=o}^{\infty} A_n \sin\left[\frac{(n + \frac{1}{2})\pi x}{s}\right]$$

So the time dependent temperature profile of the mirror is:

$$T\ (x,\ t) \ = \ T_o + (F/K)x - \frac{2Fs}{\pi^2 K} \sum_{n=o}^{\infty} \left\{ \frac{(-1)^n}{(n + \frac{1}{2})^2} \sin\left[\frac{(n + \frac{1}{2})\pi x}{s}\right] \bullet \exp\left[\frac{-(n + \frac{1}{2})^2 \pi^2 Dt}{s^2}\right] \right\}$$

The total change in mirror thickness is:

$$\Delta S(t) \ = \ \alpha \int_0^s \left[T(t,\ x) - T_o\right] dx$$

$$\Delta S(t) = \alpha F s^2/2K - 2\alpha F s^2/K\pi^3 \sum_{n=0}^{\infty} \frac{(-1)^n}{(n+\frac{1}{2})^3} \exp\left[\frac{-(n+\frac{1}{2})^2\pi^2 Dt}{s^2}\right]$$

The $n = 0$ term of the Fourier expansion clearly dominates both the temperature profile and the thermal expansion. The system therefore has an effective time constant which is equal to:

$$\tau = 4s^2/\pi^2 D$$

Table 1 compiles values of the front surface temperature rise, $(T(s,t) - T_0)$, and the thickness change of the mirror, $\Delta S(t)$, comparing their normalized values with exponential relation of the form $1-\exp(-t/\tau)$. It may be seen that the initial rise in front surface temperature is more rapid and the initial change in length is less rapid, but that they both approach the exponential relaxation for $t/\tau > 1$.

In Table 2 we compute ΔS (as $t \to \infty$), ΔT (as $t \to \infty$), and τ for three potential mirror materials; Cer-Vit, U.L.E., and beryllium. The 100 cm and 65 cm mirrors are assumed to have aspect ratios of 6:1. The temperature difference between front and back surfaces is proportional to the mirror thickness. Both the steady-state thermal expansion and time constant are proportional to the square of the mirror thickness. The energy flux, F, is assumed to be 14% of one solar constant, or 19 $mW\text{-}cm^{-2}$, which is characteristic of an aluminum mirror coating. The different values for ΔS of Cer-Vit arise from variations in quoted coefficients of thermal expansion.

In summary:

$\Delta T(t \to \infty)$	$= Fs/K$	Steady state temperature difference across mirror
$\Delta S(t \to \infty)$	$= \alpha F s^2/2K$	Steady state change in mirror thickness
τ	$= 4s^2/\pi^2 D$	Time constant

In conclusion, a beryllium mirror may exhibit thermal quality similar to that of a low-expansion glass mirror <u>if the cold plate can control the back surface temperature to < $0.1^{\circ}C$.</u> Beryllium mirrors of the desired thickness have time constants of a few minutes, low-expansion glass mirrors have time constants of a few hours.

TABLE A-1

TRANSIENT BEHAVIOR OF PLANE MIRROR

t/τ	$\dfrac{T(s, t) - T_o}{\Delta T(t \to \infty)}$	$\Delta S(t)/\Delta S(t \to \infty)$	$1 - \exp(-t/\tau)$
0.0	0.00	0.00	0.00
0.1	0.23	0.08	0.10
0.2	0.32	0.16	0.18
0.4	0.45	0.31	0.33
0.6	0.55	0.43	0.45
0.8	0.64	0.54	0.55
1.0	0.70	0.62	0.63
1.5	0.82	0.77	0.78
2.0	0.89	0.86	0.86
3.0	0.96	0.95	0.95
∞	1.00	1.00	1.00

TABLE A-2

CHARACTERISTICS OF SEVERAL POTENTIAL PRIMARY MIRROR MATERIALS

	CER-VIT	U.L.E.	BERYLLIUM
$\alpha(^{o}C^{-1})$	$(0.05 - 0.14) \times 10^{-6}$	0.06×10^{-6}	12×10^{-6}
K $(watt - cm^{-1} - {^{o}C^{-1}})$	.017	.013	2.2
C $(joule\text{-}cm^{-3} - {^{o}C^{-1}})$	2.3	1.6	3.5
α/K $(cm - watt^{-1})$	$(2.9 - 8.2) \times 10^{-6}$	4.6×10^{-6}	5.5×10^{-6}
D $(cm^{2} - watt^{-1})$	.0074	.0081	0.63
ΔT [100 cm]	$19^{o}C$	$24^{o}C$	$0.14^{o}C$
ΔT [65 cm]	$12^{o}C$	$16^{o}C$	$0.09^{o}C$
ΔS [100 cm]	770Å - 2200Å	1200Å	1400Å
ΔS [65 cm]	320Å - 900Å	510Å	610Å
τ [100 cm]	1.5×10^{4} sec (4.2 hr)	1.4×10^{4} sec (3.9 hr)	180 sec (3 min)
τ [65 cm]	6.4×10^{3} sec (1.8 hr)	5.9×10^{3} sec (1.6 hr)	75 sec

APPENDIX B

HELIOSCOPE ALIGNMENT AND IMAGE MOTION COMPENSATION TECHNIQUES

(Based on a memorandum from Dr. R. Kaul, ORI, to Dr. W. Neupert and Mr. C. Stouffer, GSFC)

Several helioscope alignment and image motion compensation (IMC) techniques have been proposed by BBRC, Itek, and JPL. The required alignments consist of correcting the decenter, tilt, and spacing between the primary and secondary mirrors due to structural changes between the mirrors and structural changes of the mirrors. The definition of these alignment errors is shown in Figure B-1 which is taken from Reference 1, page 4-15. The requirement for the alignment of the foci of the primary and secondary mirror is about 0.06 mm to insure diffraction-limited performance for the 65-cm helioscope (Ref. 1, p. 4-14). This requirement transforms into the following design requirements (similar requirements are found in Reference 3, Chapter 10):

decenter = 0.06 mm (Ref. 1, p. 4-77)
tilt = 0.1 degree (Ref. 1, p. 4-77)
axial spacing = 0.003 mm (Ref. 1, p. 4-17)
conventional tilt = 45 arc seconds (Ref. 1, p. 4-14)
conventional decenter = 0.06 mm (Ref. 1, p. 4-14)

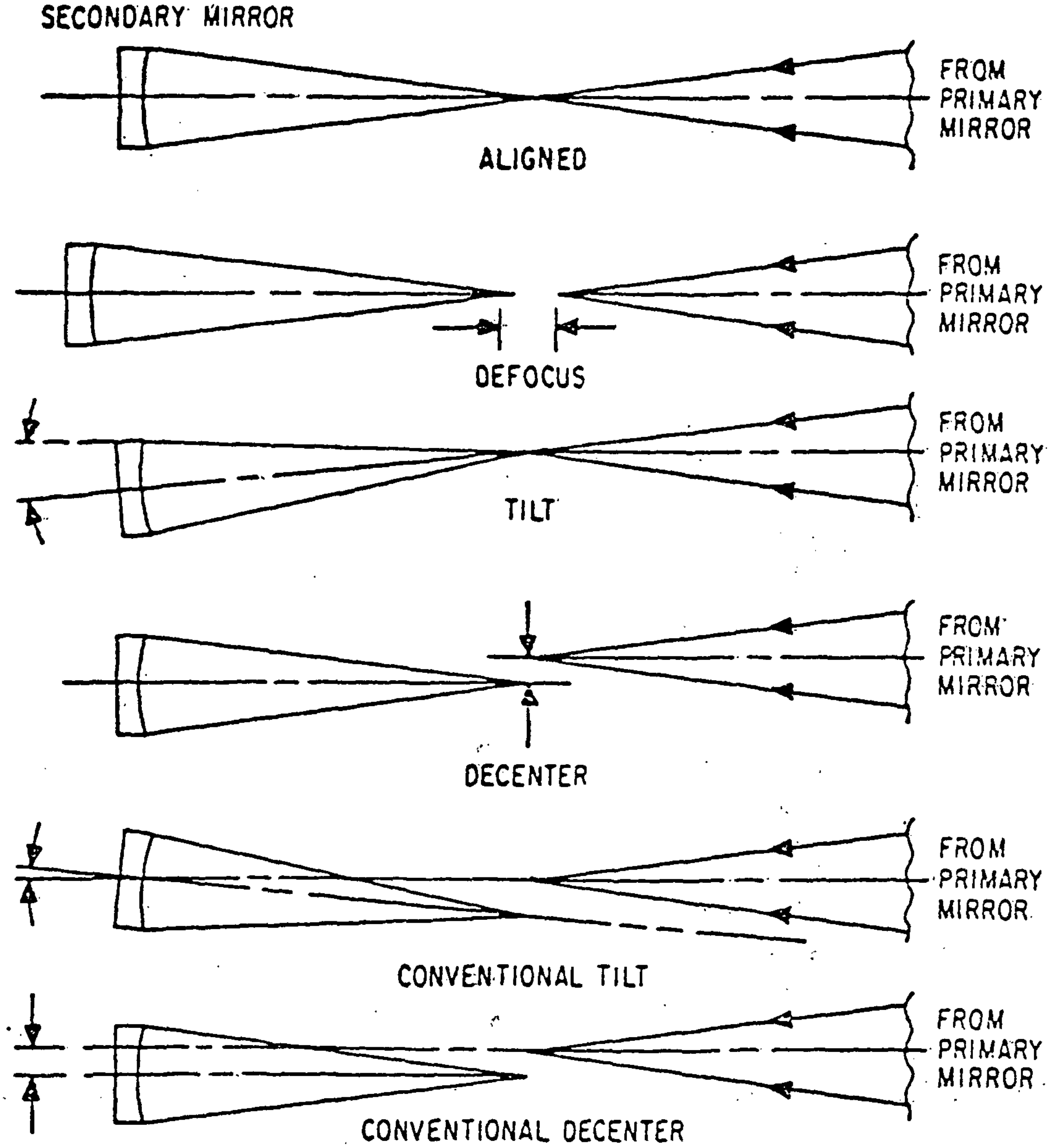


FIGURE B-1. SECONDARY MIRROR ALIGNMENT

The significant difference in the tilt results arises due to the definition of the point of rotation (see Figure 1). The axial spacing design requirement arises because of the desire to maintain the final image in the focal plane to $\pm$ 0.5 mm (Ref. 1, p. 4-17). Of course, if large excursions of the focal plane instrumentation were allowable in the axial direction, this axial spacing requirement could be relaxed.

The image motion compensation (IMC) is accomplished by articulating a relay mirror in the optical path to eliminate pointing instabilities, solar rotation (0.15 arc seconds per minute), angular rotation of the Earth about the Sun (2.4 arc seconds per minute) and orbital velocity of the vehicle about the Earth (0.5 arc second per minute).

Ball Brothers Research Corporation Suggested Alignment Technique

The suggested technique for correcting the alignment of the telescope is to reposition the secondary mirror pod for decenter and tilt correction and reposition the secondary mirror within the pod for focus control (Ref. 2, p. 4-26). The decenber and tilt corrections are monitored by shining a laser diode source on two sets of detectors - 4 edge detectors and a quadrant cell detector. A schematic of the system is shown in Figure B-2 (Ref. 2, p. 4-28) and Figure 3 (Ref. 2, p. 4-29) shows the angles and displacements associated with the tilt and decentration errors. The decenter offset δ is directly proportional to ε and this is measured by the quadrant detector. The tilt error θ is:

$$\theta = \frac{\Delta + \delta}{F}$$

so θ must be computed from the outputs of the edge and quadrant detector. The computation is done by a passive circuit since F is a constant. This alignment system (without closing the feedback loop) has been breadboard at BBRC and operated successfully.

The image focus control (IFC) proposed by BBRC measures a spatial frequency scan of the modulation transfer function (MTF) monitored by the image dissector tube (IDT) mounted at the focal plane as shown in Figure 4 (Ref. 2, p. 4-31). The closed loop system operates by modulating the focus position of the image via an axial displacement of a relay lens mounted in

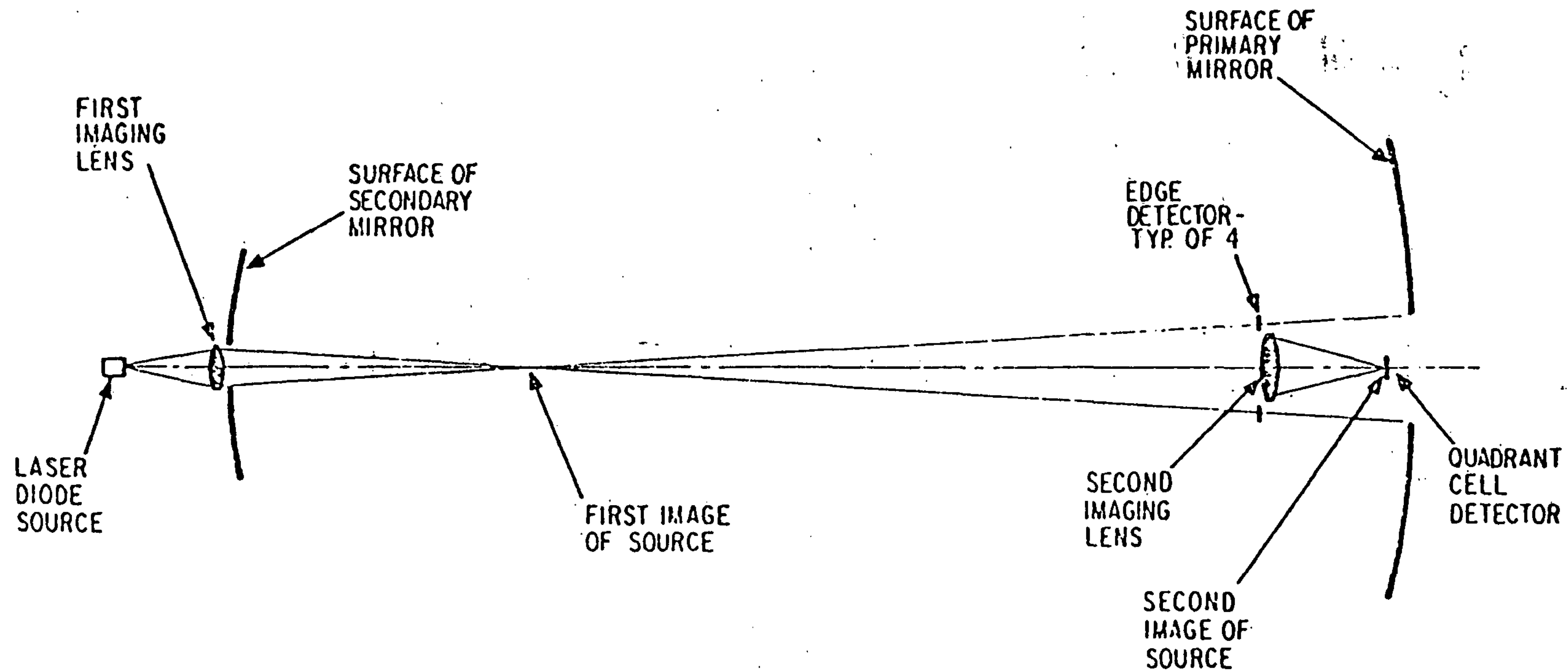
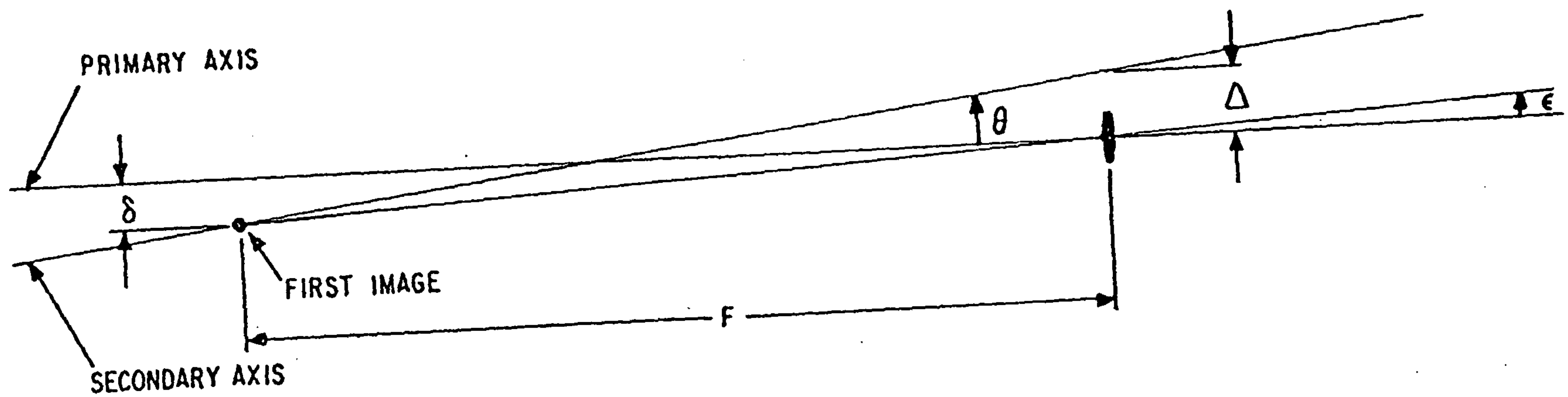


FIGURE B-2. INTERNAL ALIGNMENT SCHEME



$$\delta = \epsilon F$$

$$\theta = \frac{\Delta + \delta}{F}$$

FIGURE B-3. PRIMARY - SECONDARY ALIGNMENT SCHEME

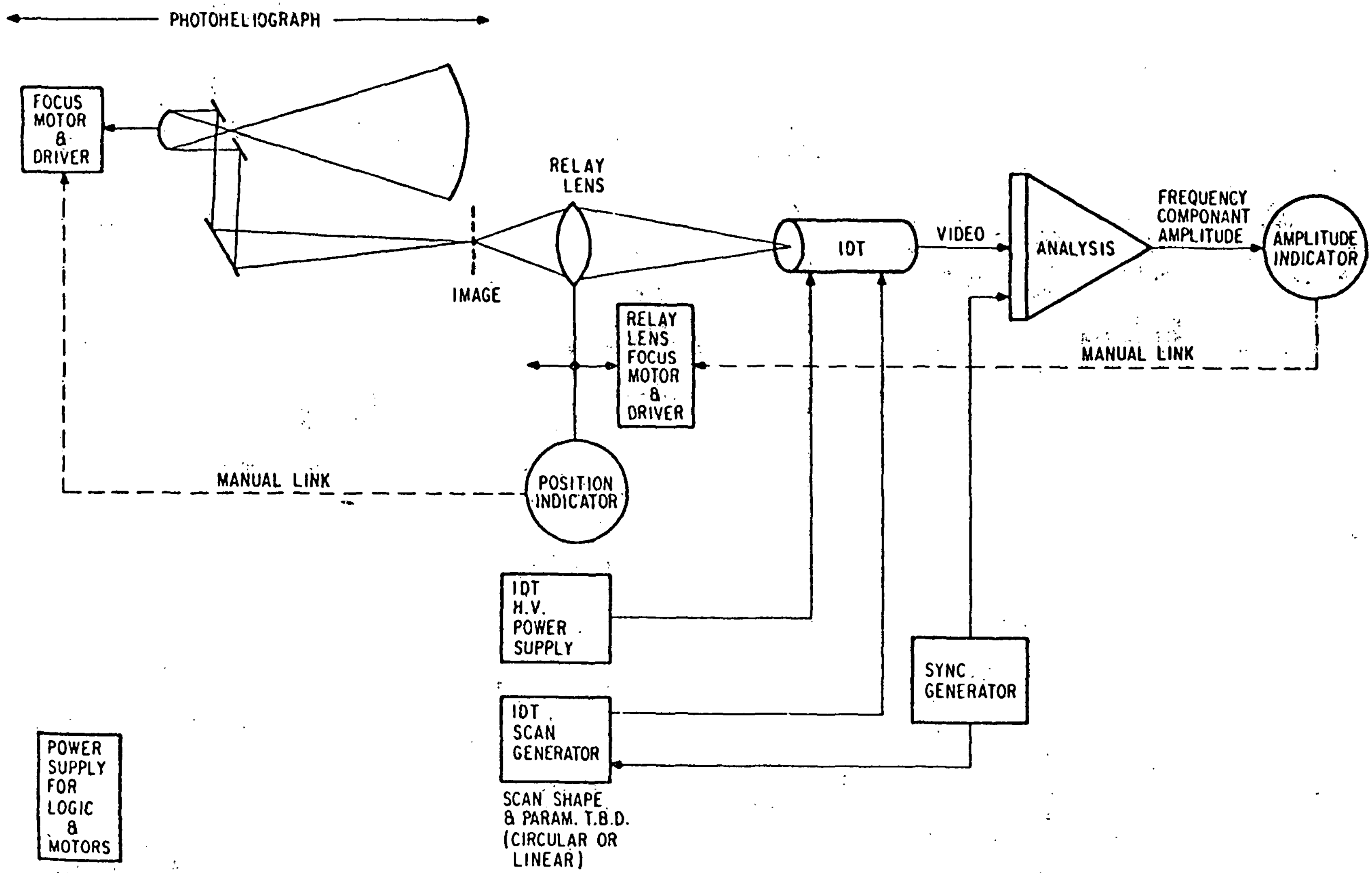


FIGURE B-4. FUNCTIONAL DIAGRAM OF FOCUS SYSTEM

front of the IDT. When the MTF is maximized the "best" focus is obtained. If a "best" focus is not obtained the secondary mirror is driven along the optical axis until best focus is obtained.

The IFC system was breadboarded at BBRC and successfully operated using a "picket fence" bar pattern. However, attempts to operate the system on transparencies of the sun were unsuccessful because of insufficient signal at the selected spatial frequency for maximum focus sensitivity. At lower spatial frequencies, there was only a low focus sensitivity, and therefore proof-of-principle via simulation of the sun was not obtained (Ref. 2, p. 4-33).

Ball Brothers Research Corporation Suggested Image Motion Compensation Technique

The IMC technique proposed by BBRC utilizes many of the same techniques employed in the image focus system. The vertical and horizontal scans of the image focussed on an IDT are Fourier analyzed and the magnitudes of the coefficients are measured as a function of position. The second tilting mirror is then gimballed to maintain these coefficient amplitudes in a fixed position with respect to the face of the IDT. The mathematical analysis of the viability of this IMC system has been presented in some detail in Reference 1, pages 4-93 and 5-38. A breadboard of one version of an IMC, similar to the unit shown in Figure 5 (Ref. 2, p. 4-34), has been built by the Bendix Corporation and furnished to NASA/MSFC for evaluation on the existing Big Bear Solar Observatory helioscope (Ref. 2, p. 4-33).

Itek Suggested Alignment Concept

Itek recommends movements of the secondary mirror structure rather than the primary mirror because of changes in the helioscope boresight and because the secondary mirror is much smaller and lighter than the primary. A three actuator, 3 flexure point A-frame configuration with sequential on-off actuator operation is recommended for tilt, decenter and focus realignments (Ref. 3, p. 9-20). The actuator system would be capable of accommodating axial and longitudinal structural changes from the primary to secondary of $\pm$ 0.12 cm.

The recommended decenter monitor is a primary mirror-mounted sensor/ detector assembly focussed on a spherical mirror at the center of the secondary.

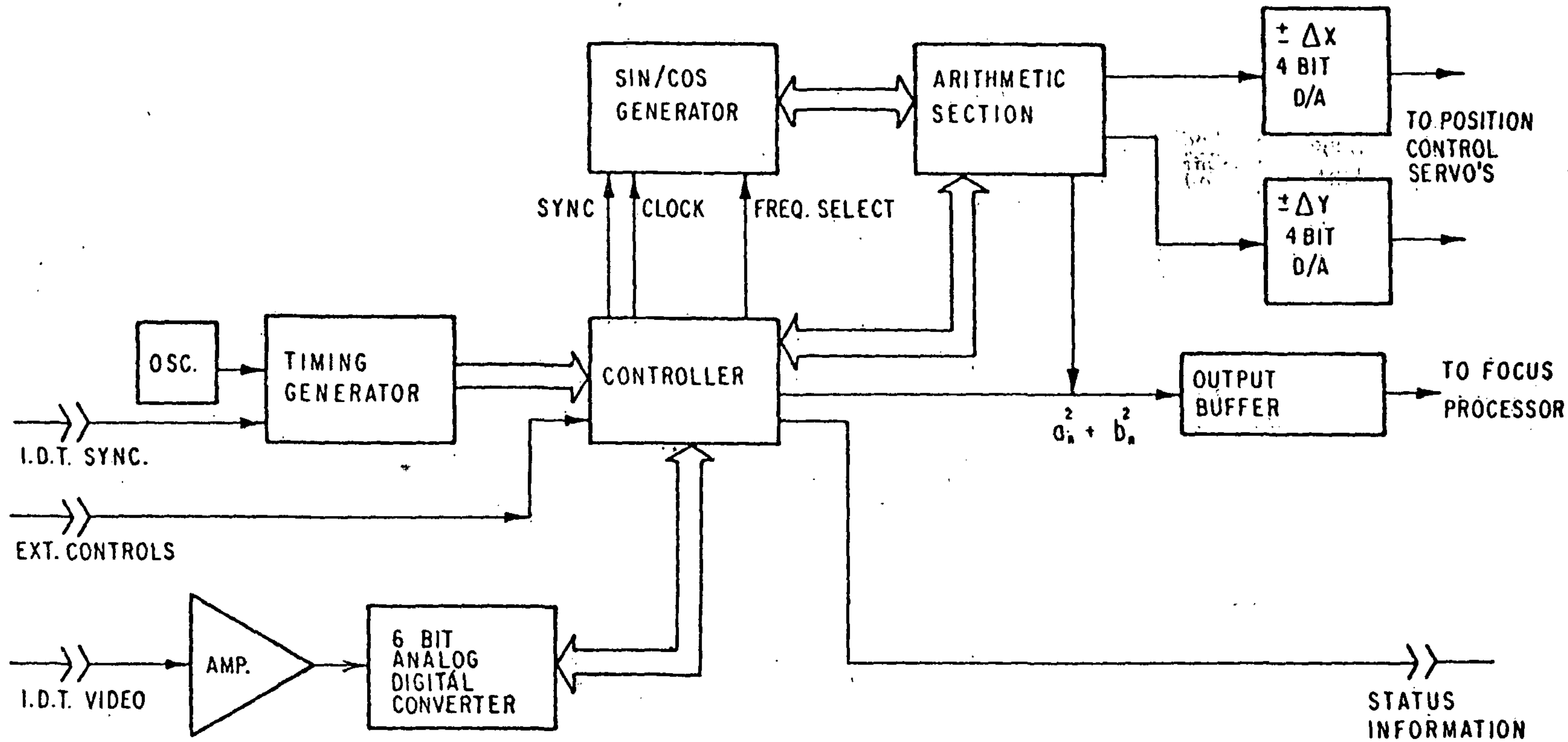


FIGURE B-5. IMAGE MOTION PROCESSOR BLOCK DIAGRAM

The primary mirror-mounted light source consists of a GaAs diode illuminating the truncated apex of a pyramidal reflector. The sensor objective reimages the apex at a point at the center of curvature of the spherical mirror on the secondary (Ref. 3, p. 9-14). The decentered light beam is then reimaged by the relay optics and detected by the four photo-diodes mounted in quadrature. The assembly is shown schematically in Figure 6 which is a modification of Figure 9-5 of Ref. 3. Itek has operated decenter systems similar to the system shown in Fiugre 6 over a 3 meter distance and has attained a null stability of 1 micrometer per meter of separation and a long term stability of 1 to 2 micrometers per meter (Ref. 3, pp. 9-14 and 9-16).

For the tilt sensor Itek recommends a commercial automatic autocollimator of less accuracy and smaller size than the system in Figure 6 utilizing a flat mirror on the secondary (Ref. 3, p. 9-20).

For focus control Itek recommends utilizing a Focatron-type detector, Itek's vidicon type, a modification of an image correlation device, or a scanning recticle type of system (Ref. 3, p. 9-14). The Focatron system uses a nonlinear photodiode whose output is minimized when the dark lines between granules are in focus compared to the more even distribution of light when the image is out-of-focus (see J. C. Bliss and H. D. Crane, Optical and Electro-Optical Informaiton Processing, M.I.T. Press, Cambridge, Mass.). The Itek vidicon type was not described. The modified IMC system has been described by BBRC earlier in this memor, and the scanning reticle system detects the light output from a scanned reticle in the image place (see J. Simon, Applied Optics, 9, 2337, October, 1970). A detailed application study of the above candidate systems still needs to be carried out for the simulated solar scene (Ref. 3, p. 9-14).

Itek Suggested Image Motion Compensation Concept

Itek identified the requirement for both a sun limb sensor and a correlation tracker. When using the sun limb sensor the roll of the telescope would be stabilized by a star tracker directed approximately perpendicular to the helioscope axis. The sun limb sensor is used for acquisition and for offset pointing to a particular region of the sun, and then the correlation tracker is switched into operation. The diagram of how the pitch and yaw control system operates is shown in Figure 7 (Ref. 3, p. 7-14).

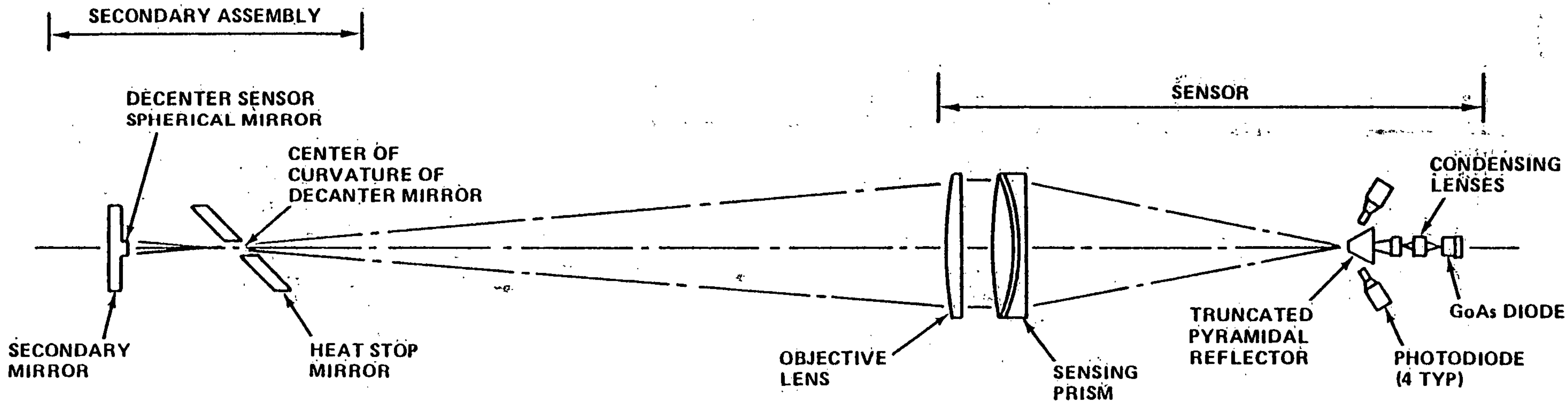


FIGURE B-6. ITEK DECENTER DETECTOR OPTICAL LAYOUT

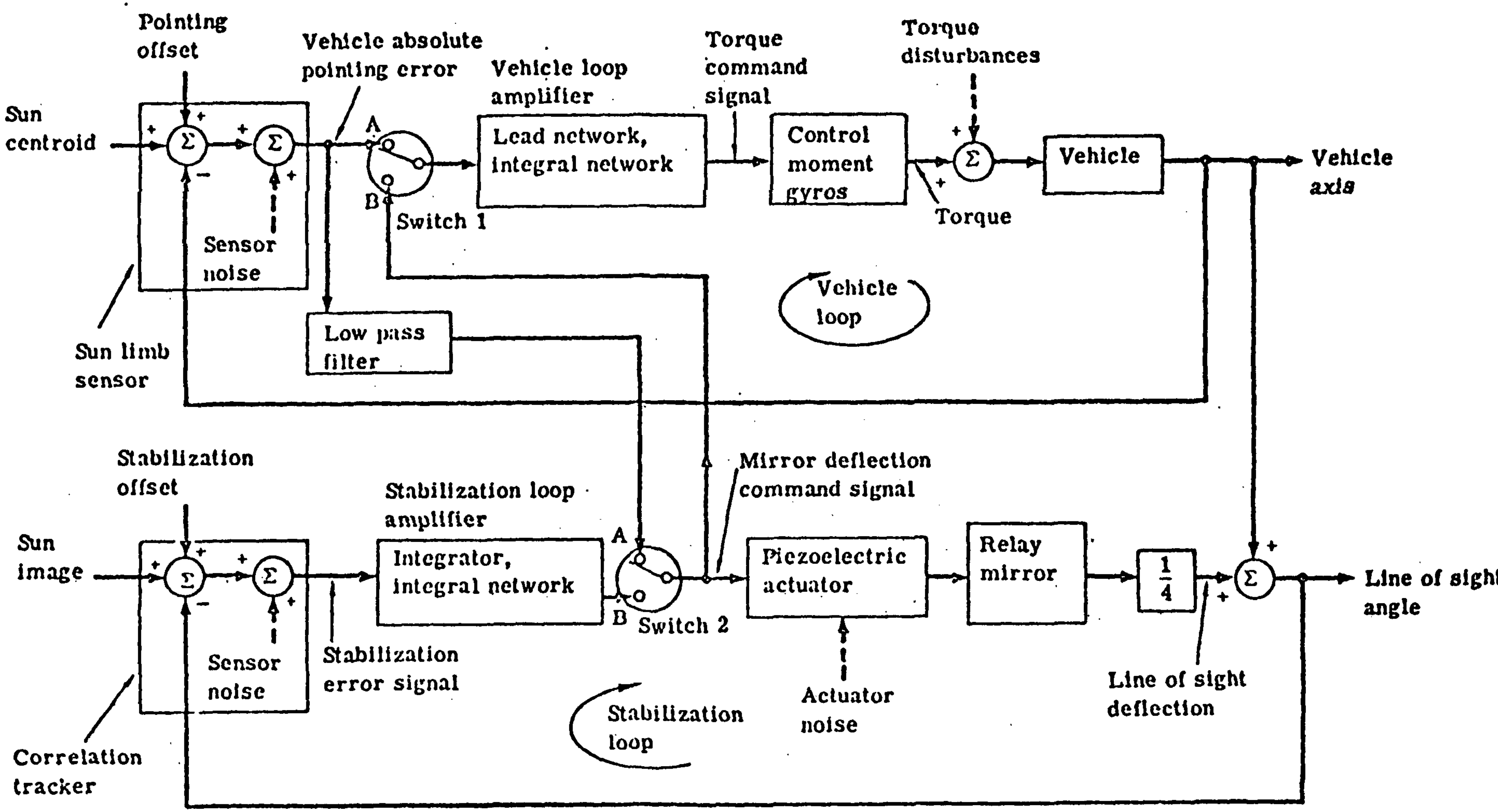


FIGURE B-7. POINTING AND STABILIZATION IN PITCH OR YAW

The correlation tracker would have a 10 to 20 arc second field of view out of the 4 arc minute helioscope field of view (FOV). It was decided that the tracker FOV should be movable within the helioscope FOV since when examining certain regions of the sun, such as solar flares, the granules will not provide a good signal to noise level signal (Ref. 3, p. 7-15).

Itek has built a correlation tracking system (EC-6) consisting of an image dissector which is used for photographic imagery. The dissector scans the image with a resolution equivalent to 31 television lines (a 21 millimeter field). The measured rms tracking error was 10 micrometers of 1/1200 of the total imagery field. The solar image from the helioscope will match the dissector quite closely so that tracking on the granule lines should be possible with a stability of 0.008 arc second rms (Ref. 3, p. 7-11).

<u>Jet Propulsion Laboratory Alignment and IMC Techniques</u>

The Jet Propulsion Laboratory (JPL) alignment technique is described in Ref. 4. The system employs a side-mounted detector system near the edge of the primary mirror, a combination beam splitter/spherical mirror mounted at the center of the primary mirror, and a "pinlite" and spherical mirror mounted at the center of the secondary mirror. This system had the disadvantage (compared to the BBRC and Itek designs) of requiring a roll alignment between the detector and the beam splitter on the primary mirror, because the detector is side-mounted. Analysis indicated that the system was capable of detecting helioscope tilt and decenter misalignments with sufficient accuracy to maintain "diffraction-limited" operation.

Only a limited amount of focus sensing work was done prior to termination of the JPL helioscope contract (Ref. 5, p. 56). JPL planned on moving the focal plane instrumentation by monitoring the MTF of the scene and telescope.

<u>Status of Helioscope Alignment and IMC Technology</u>

Clearly the proof-of-principle for the control of the decentration and tilt of the secondary mirror with respect to the primary mirror has been demonstrated by Itek. However, the question remains as to whether the decenter and tilt can be implemented on a helioscope when large amounts of scattered light are creating noise signals.

The focus control systems have not been tested on a helioscope, and thus additional study is required in this area. BBRC has a breadboard system, but it appears that because of the difficulty in simulating the solar granules on earth, the tests were terminated. Possibly a study of how to simulate the dynamics of the solar surface is required in order to evaluate helioscope subsystems on earth.

Future IMC studies should await the results of tests of the IMC unit furnished to NASA/MSFC by Bendix Corp. The results of these tests may resolve many questions regarding the practicability of testing helioscope IMC systems on earth.

TABLE B-1

REFERENCES

1. CIT Photoheliograph Definition Study, Final Report, Vol. II, by Ball Brothers Corporation for NASA/MSFC, Contract No. NAS8-30190, April 1971.

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3. Photoheliogrpah Definition Study, Final Report, Vol. II, Books I and II, by Itek Optical Systems Division for NASA/MSFC, Contract No. NAS8-28147, 8 January 1973.

4. Photoheliograph Alignment System, Document 750-11, Rev. A, by the Jet Propulsion Laboratory under Contract NAS7-100, October 17, 1968.

5. Photoheliogrpah Optical System, Document 750-8, Rev. A, by the Jet Propulsion Laboratory, December 15, 1968.